Volodymyr Magas

An improved unitarization method and a search for molecular-type hidden charm pentaquarks

Collaborators: *Erick Garcia Gonzalez, Angels Ramos* (UB)

Universitat de Barcelona

ICCUB

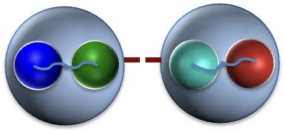
- 1 -

Exotic hadrons
(anything that goes beyond $q\bar{q}$ and qqq)

Mesons

compact tetraquark

Glueball

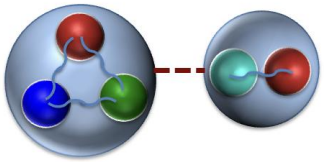


meson-meson molecule

hybrid

Baryons

compact pentaquark



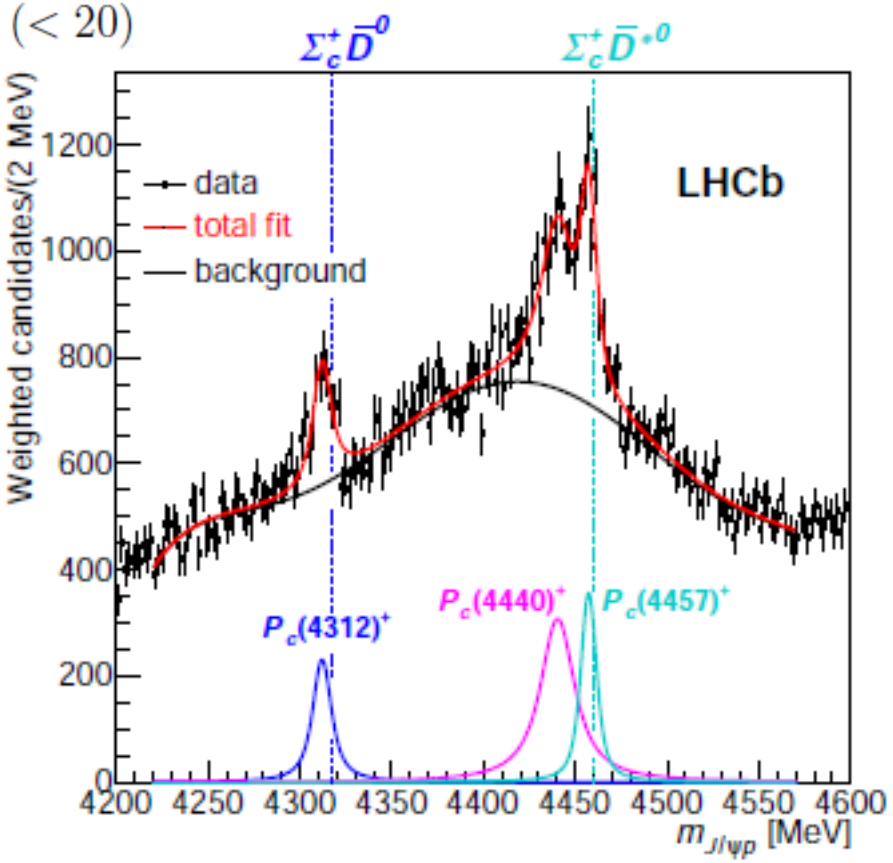
baryon-meson molecule

Since the beginning of 2000s, an increasing amount of data in the (hidden/open) charm sector (collected at Belle, BaBar, LHCb and BESIII…), has provided **evidences** for many new **exotic** states, which appear to be inconsistent with the conventional quark model

More detailed reanalysis of the pentaquark states in $\Lambda_b \to J/\psi\ K^-\ p$ decays

LHCb Coll., Phys.Rev.Lett. 122 (2019) 222001

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)



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The flavor content of the $P_c(4310)$, $P_c(4440)$, $P_c(4457)$ states is not exotic (uud), but the high mass and the observation from **J/ψ p** pairs makes them to be unambiguous pentaquark candidates ($c\bar{c}uud$)

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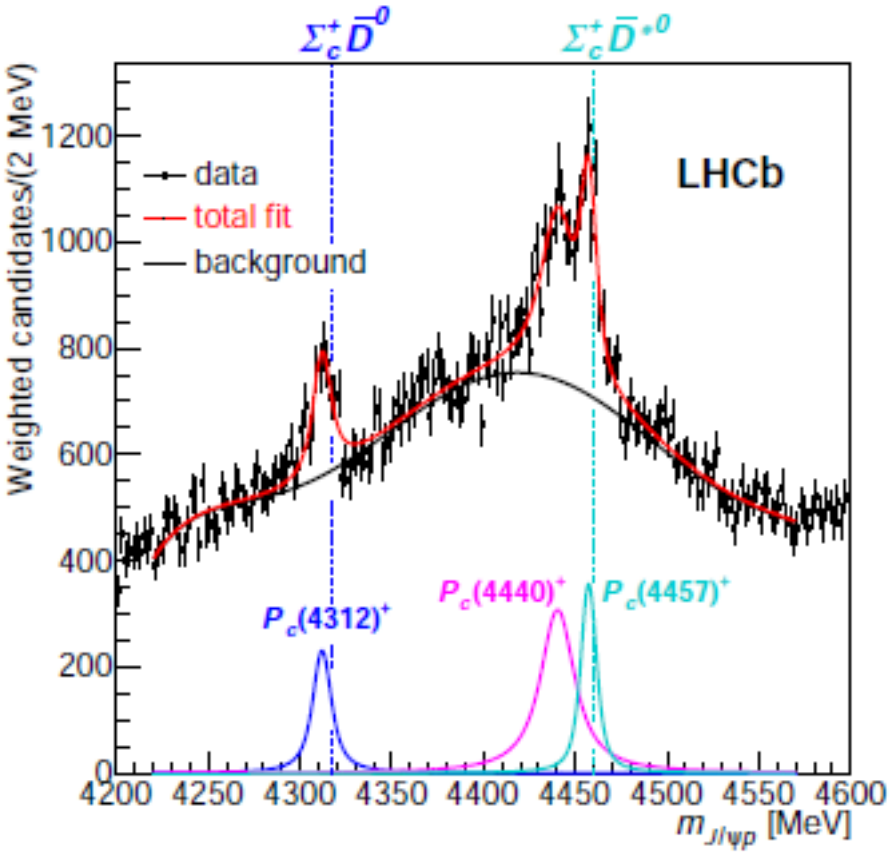


These states find a natural explanation as baryon-meson molecules:

$\bar{D}^0\Sigma_c^+$ threshold: 4318 MeV → **$P_c(4312)$**

$\bar{D}^{*0}\Sigma_c^+$ threshold: : 4460 MeV → **$P_c(4440)$, $P_c(4457)$**

and were already predicted in 2010!

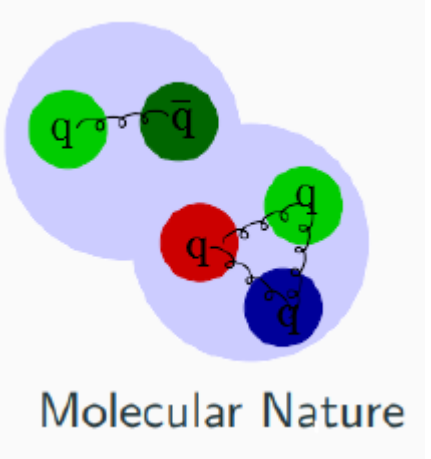
Exotic baryons

P_c or P_Ψ^N S=0 $(c\bar{c}qqq)$, $q = u, d$

Molecular models

- Wu, Molina, Oset, Zou,
  PRL 105, 232001 (2010); PRC 84, 015202 (2011)

- Yang, Sun, He, Liu, Zhu**, Chin. Phys. C 36, 6 (2012)**
- Xiao, Nieves, Oset, **PRD 88, 056012 (2013)**
- Karliner, Rosner, **PRL 115, 122001 (2015)**

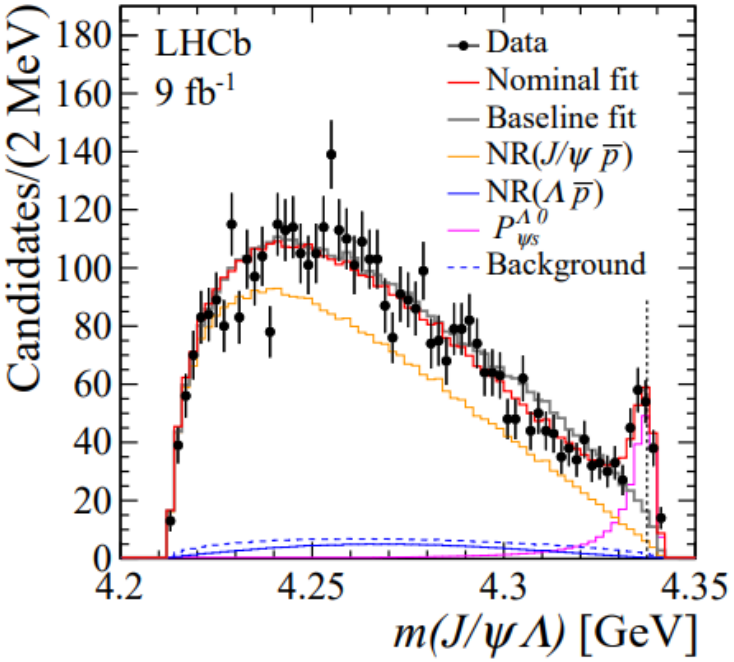


Exotic baryons

P_{cs} or $P^{\Lambda}_{\psi s}$ **S=-1** $(c\bar{c}qqs)$, $q = u, d$

$B^- \to J/\psi \Lambda \bar{p}$

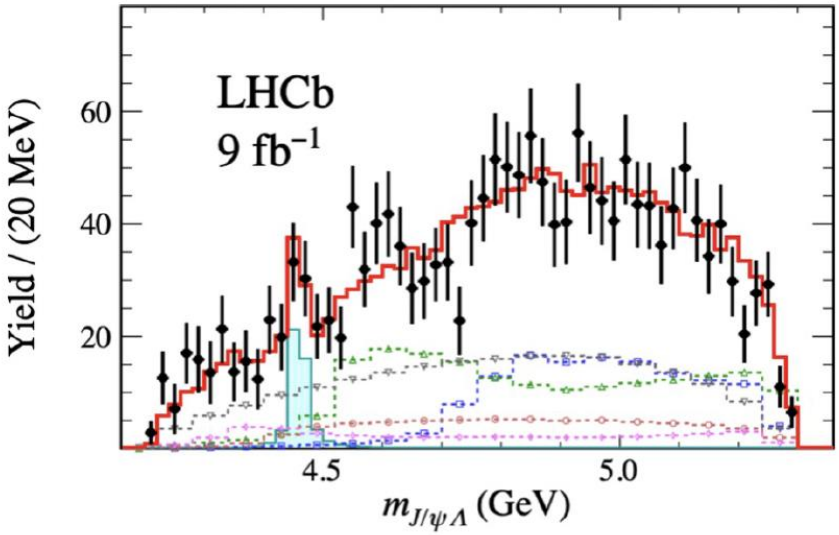
LHCb, PRL 131 (2023) 3, 031901



$P_{cs}(4338)$

$\Xi_b^- \to J/\psi \Lambda K^-$

LHCb, Sci. Bull. 66 (2021) 1278



$P_{cs}(4459)$

Exotic baryons

P_{css} or $P^{\Xi}_{\psi ss}$ **S=-2** $(c\bar{c}qss)$, $q = u, d$

S=-2 pentaquarks?

Exotic baryons

P_{css} or $P^{\Xi}_{\psi ss}$ S=-2 $(c\bar{c}qss)$, $q = u, d$

S=-2 pentaquarks?

Some theoretical studies predict molecular-type states

Marsé-Valera, Ramos, Magas,
PRL **130** (2023) 9; PRD **111** (2025) 5, 5

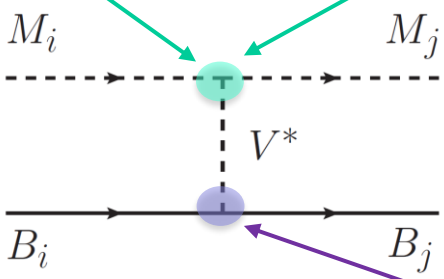
Roca, Song, Oset, PRD 109, 094005 (2024)

Unitarized t-channel vector-meson exchange interaction

$$\mathcal{L}_{VPP} = -ig\langle[\phi, \partial_\mu \phi]V^\mu\rangle$$

$$\mathcal{L}_{VVV} = ig\langle[V^\mu, \partial_\nu V_\mu]V^\nu\rangle$$

Effective Chiral Lagrangian



$$\mathcal{L}_{VBB} = \frac{g}{2} \sum_{i,j,k,l=1}^{4} \bar{B}_{ijk}\gamma^\mu \left(V^k_{\mu,l} B^{ijl} + 2V^j_{\mu,l} B^{ilk}\right)$$

Unitarized t-channel vector-meson exchange interaction

$$\mathcal{L}_{VPP} = -ig\langle[\phi, \partial_\mu \phi]V^\mu\rangle$$

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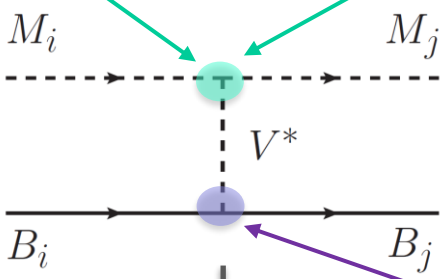

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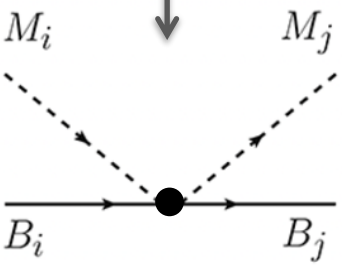
S-wave

$t \ll m_{V^*}^2$



Interaction kernel

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

The only model parameter is **pion decay constant, $f = af_\pi$**

S=-2 sector

Interaction kernel

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

	$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$	$\eta'\Xi$	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
$\pi\Xi(1456)$	2	$\frac{3}{2}$	$\frac{1}{2}$	0	0	0	0	0	$\sqrt{\frac{3}{2}}\kappa_c$
$\bar{K}\Lambda(1611)$		0	0	$-\frac{3}{2}$	0	0	$-\frac{1}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
$\bar{K}\Sigma(1689)$			2	$\frac{3}{2}$	0	0	$\frac{3}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
$\eta\Xi(1866)$				0	0	0	κ_c	$\frac{1}{\sqrt{3}}\kappa_c$	$\frac{1}{\sqrt{6}}\kappa_c$
$\eta'\Xi(2276)$					0	0	$\frac{1}{\sqrt{8}}\kappa_c$	$-\frac{1}{\sqrt{6}}\kappa_c$	$\frac{1}{\sqrt{3}}\kappa_c$
$\eta_c\Xi(4302)$						0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c(4437)$							$-1+\kappa_{cc}$	0	0
$\bar{D}_s\Xi'_c(4545)$								$-1+\kappa_{cc}$	$-\sqrt{2}$
$\bar{D}\Omega_c(4565)$									κ_{cc}

$$\kappa_c = \frac{m_\rho^2}{m_{D^*}^2} \sim \frac{1}{4}$$

$$\kappa_{cc} = \frac{m_\rho^2}{m_{J/\psi}^2} \sim \frac{1}{9}$$

Local hidden gauge approach assuming SU(4) flavour symmetry

S=-2 sector

Interaction kernel

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

		$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$	$\eta'\Xi$	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
light sector	$\pi\Xi(1456)$	2	$\frac{3}{2}$	$\frac{1}{2}$	0	0	0	0	0	$\sqrt{\frac{3}{2}}\kappa_c$
	$\bar{K}\Lambda(1611)$		0	0	$-\frac{3}{2}$	0	0	$-\frac{1}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
	$\bar{K}\Sigma(1689)$			2	$\frac{3}{2}$	0	0	$\frac{3}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
	$\eta\Xi(1866)$				0	0	0	κ_c	$\frac{1}{\sqrt{3}}\kappa_c$	$\frac{1}{\sqrt{6}}\kappa_c$
	$\eta'\Xi(2276)$					0	0	$\frac{1}{\sqrt{8}}\kappa_c$	$-\frac{1}{\sqrt{6}}\kappa_c$	$\frac{1}{\sqrt{3}}\kappa_c$
heavy sector	$\eta_c\Xi(4302)$						0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
	$\bar{D}_s\Xi_c(4437)$							$-1+\kappa_{cc}$	0	0
	$\bar{D}_s\Xi'_c(4545)$								$-1+\kappa_{cc}$	$-\sqrt{2}$
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$$\kappa_c = \frac{m_\rho^2}{m_{D^*}^2} \sim \frac{1}{4}$$

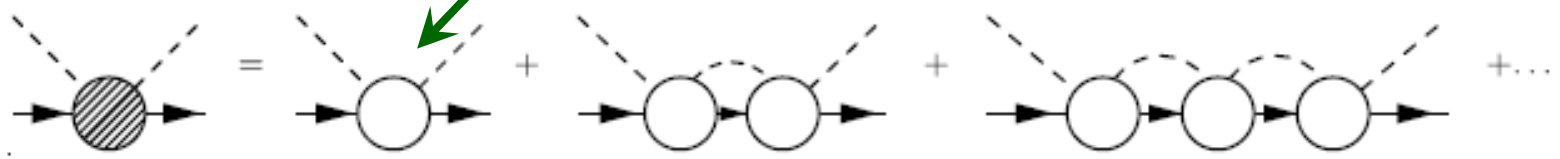
$$\kappa_{cc} = \frac{m_\rho^2}{m_{J/\psi}^2} \sim \frac{1}{9}$$

Light and heavy sectors are practically "decoupled"

Unitarization via coupled channels

Interaction kernel V_{ij}

Scattering amplitud T_{ij}



Bethe-Salpeter equation

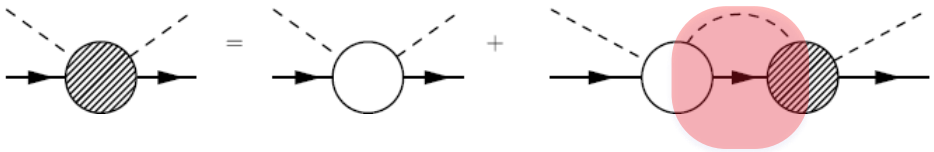
On shell factorization

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj} \quad \Rightarrow \quad T = (1 - VG)^{-1} V$$

System of the algebraic equations

Unitarization via coupled channels: Loop function

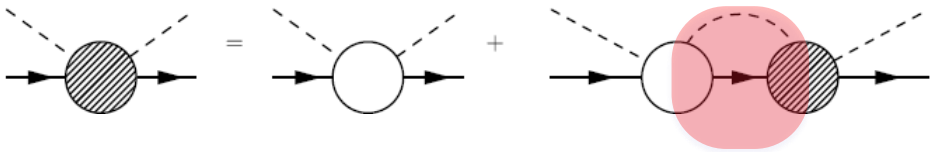
$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}$$



$$G_l = i \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \frac{2M_l}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

Loop function regularization

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}$$



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dim reg. cut-off

$$G_l^{\mathrm{DR}} = \frac{1}{16\pi^2}\left\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} + \right.$$
$$+ \frac{q_l}{\sqrt{s}}\left[\ln\left(s + (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right)\right.$$
$$+ \ln\left(s - (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right)$$
$$- \ln\left(-s - (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right)$$
$$\left.\left. - \ln\left(-s + (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right)\right]\right\}$$

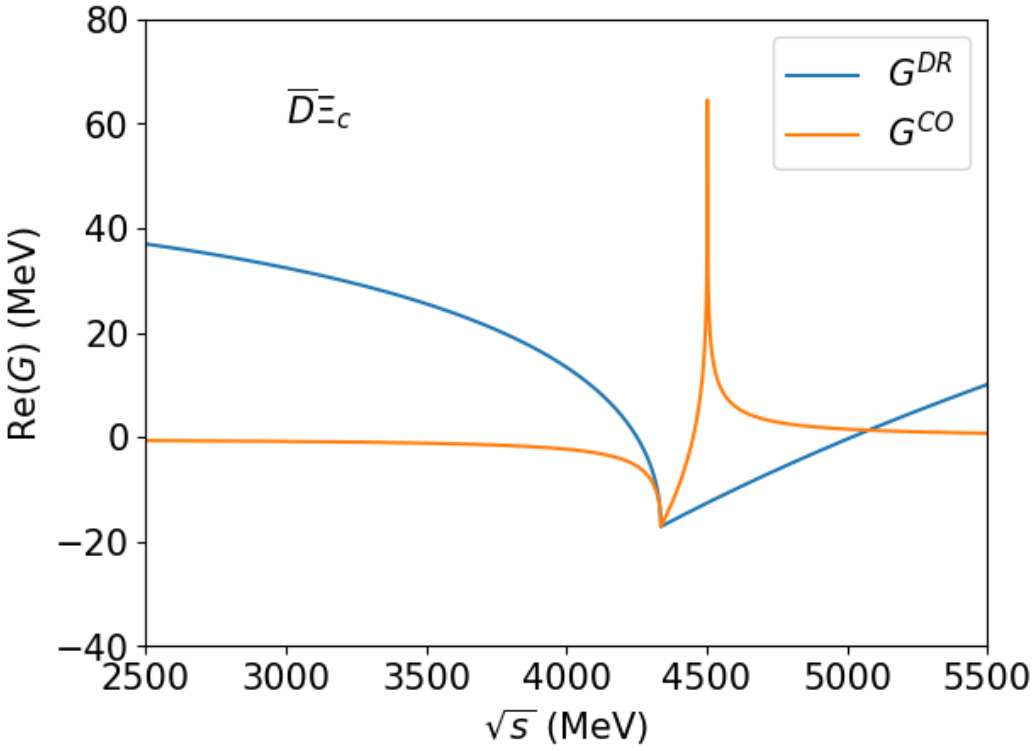
$$G_l^{\mathrm{cut}} = 2M_l \int^{\Lambda} \frac{q^2\,\mathrm{d}q}{4\pi^2} \frac{(\omega_l + E_l)}{\omega_l E_l} \frac{1}{s - (\omega_l + E_l)^2 + \mathrm{i}\epsilon}$$

$\Lambda = 600 - 1000$ MeV

$a_l(\mu) \simeq -2$ → "natural size" (μ=630 MeV)

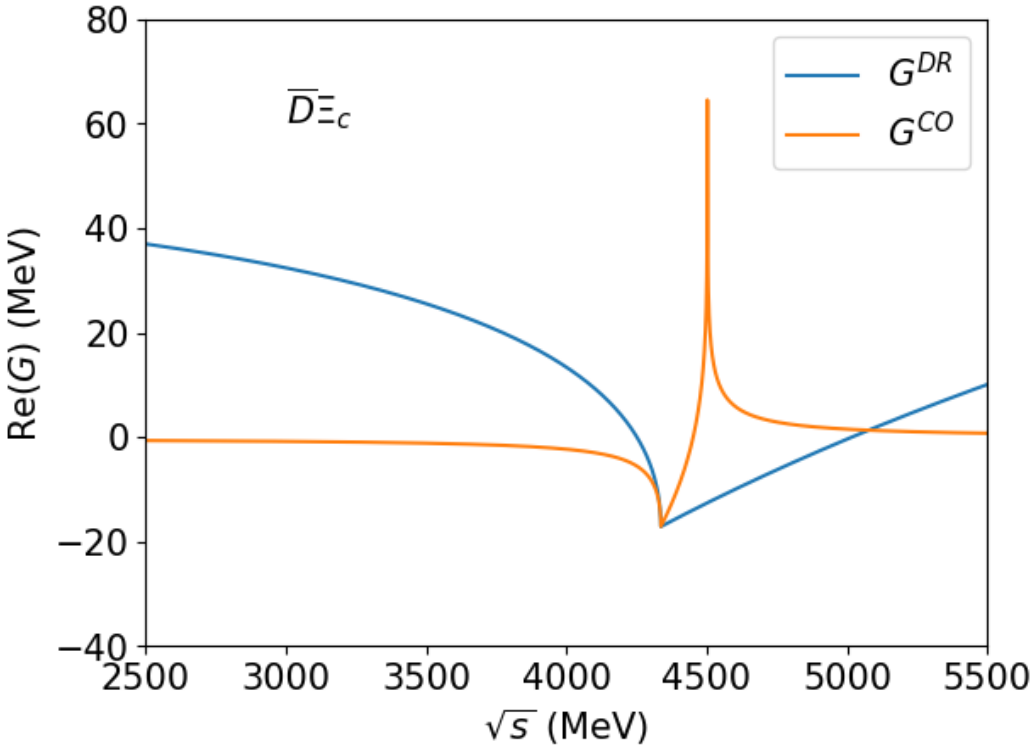
[Oller and Meissner, PL B500 (2001) 263]

Loop function regularization



$$a_l(\mu) = \frac{16\pi^2}{2M_l}\left(G_l^{\rm cut}(\Lambda) - G_l^{\rm DR}(\mu, a_l = 0)\right)$$

Loop function regularization

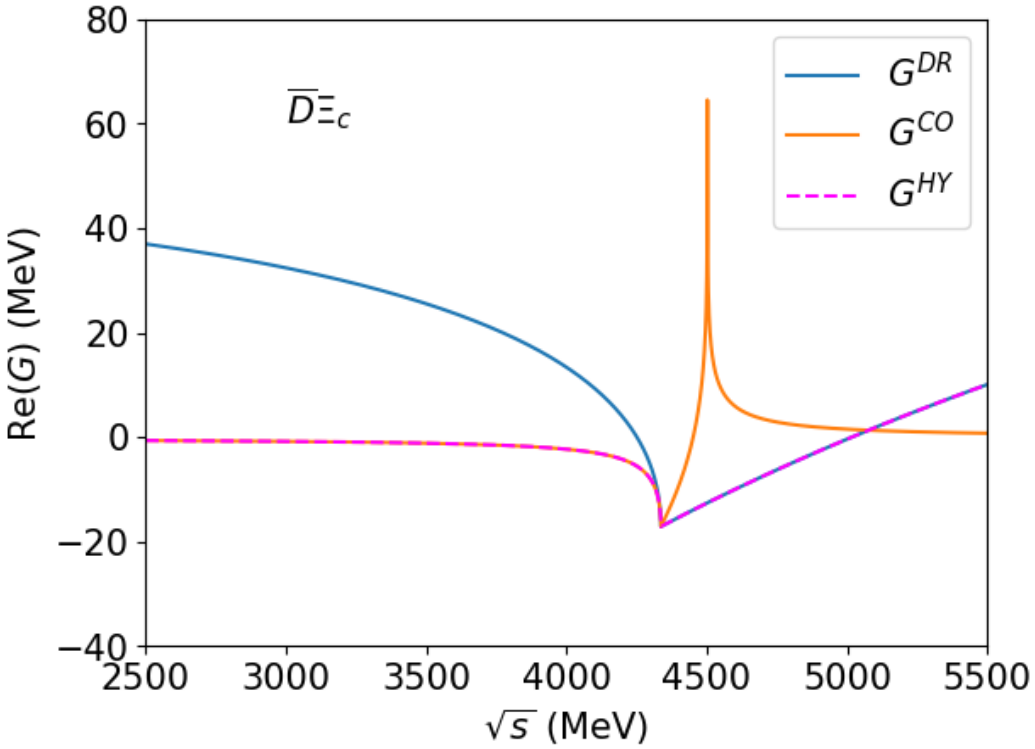


$$T = (1 - VG)^{-1}V$$

Poles: $\det(1 - VG) = 0$

Uncoupled approach:
$\mathrm{Re}(G) \sim V^{-1}$

Loop function regularization



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Erick Garcia Gonzalez,
Master Thesis, UB, July 2025
+ in preparation for Phys. Rev.

Hybrid Loop:

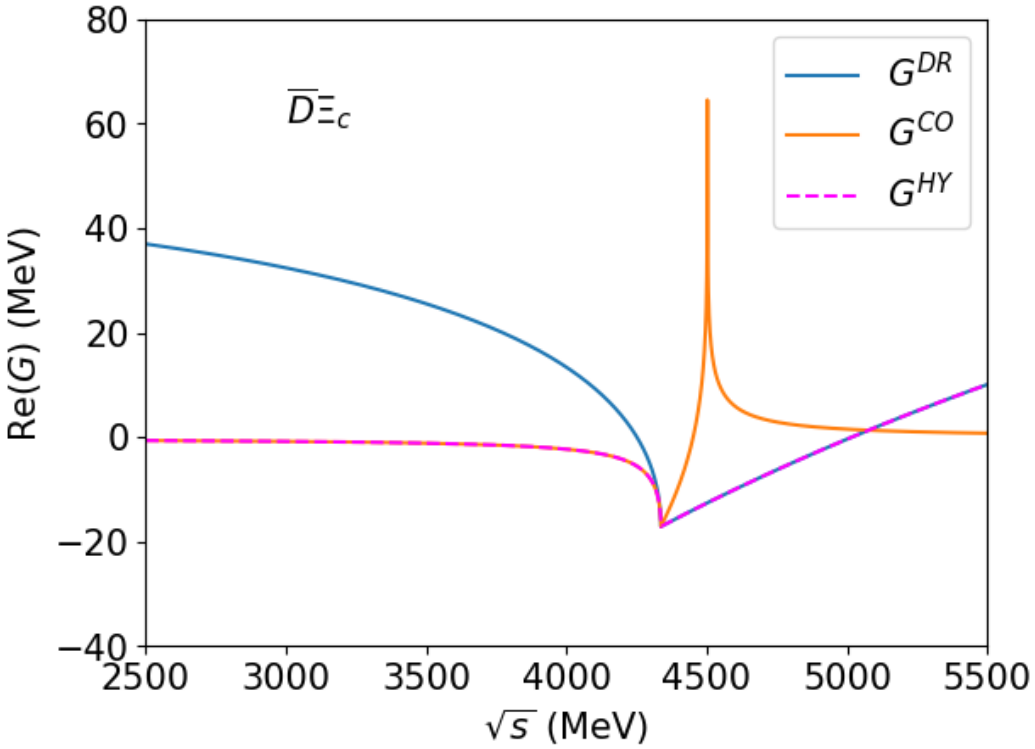
$$\mathrm{Re}(G_k^{\mathrm{HY}}) = \begin{cases} \mathrm{Re}(G_k^{\mathrm{CO}}) & if \quad \sqrt{s} < M_k + m_k \\ \mathrm{Re}(G^{\mathrm{DR}}) & if \quad \sqrt{s} \geq M_k + m_k \end{cases}$$

$$\mathrm{Im}(G_k^{\mathrm{HY}}) = \mathrm{Im}(G_k^{\mathrm{DR}})$$

$$a_l(\mu) = \frac{16\pi^2}{2M_l}\left(G_l^{\mathrm{cut}}(\Lambda) - G_l^{\mathrm{DR}}(\mu, a_l = 0)\right)$$

$$\Lambda = 600 \text{ MeV}$$

Loop function regularization



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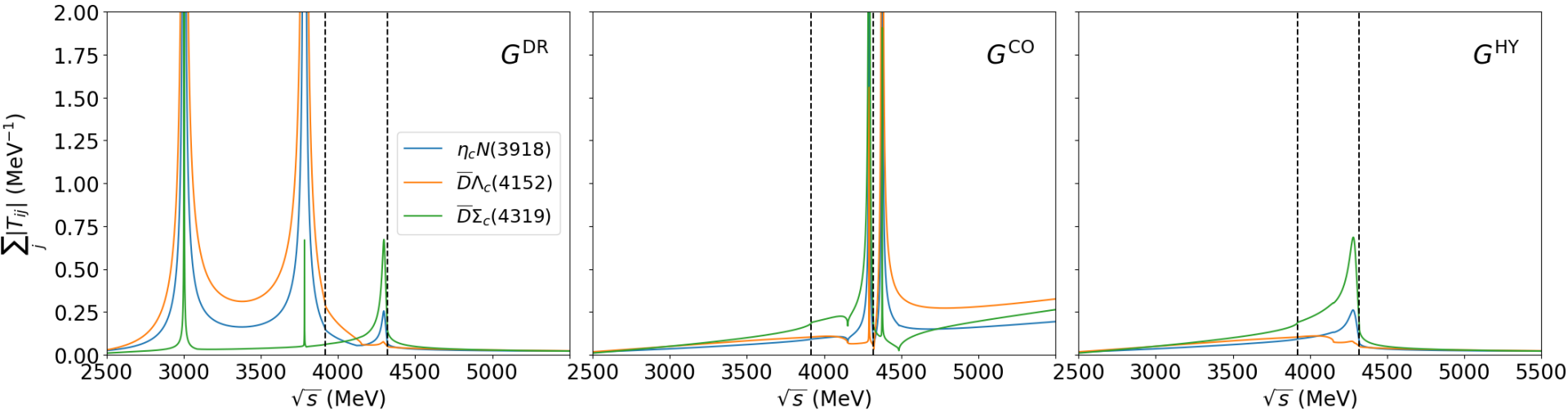
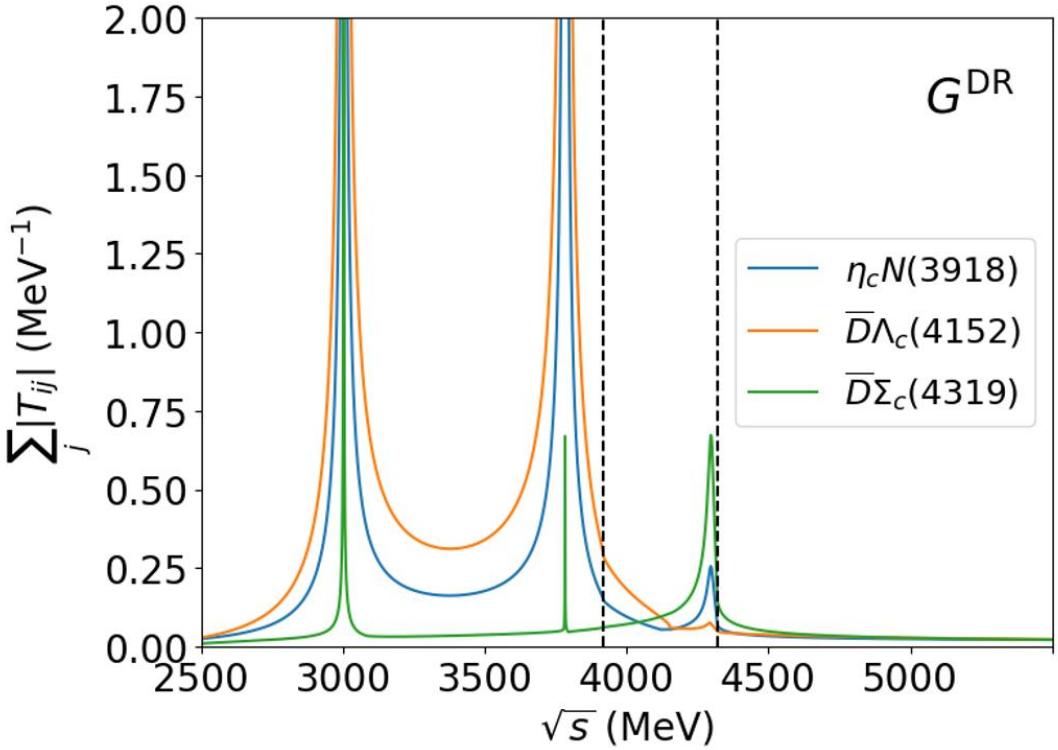
$$\mathrm{Im}(G_k^{\mathrm{HY}}) = \mathrm{Im}(G_k^{\mathrm{DR}})$$

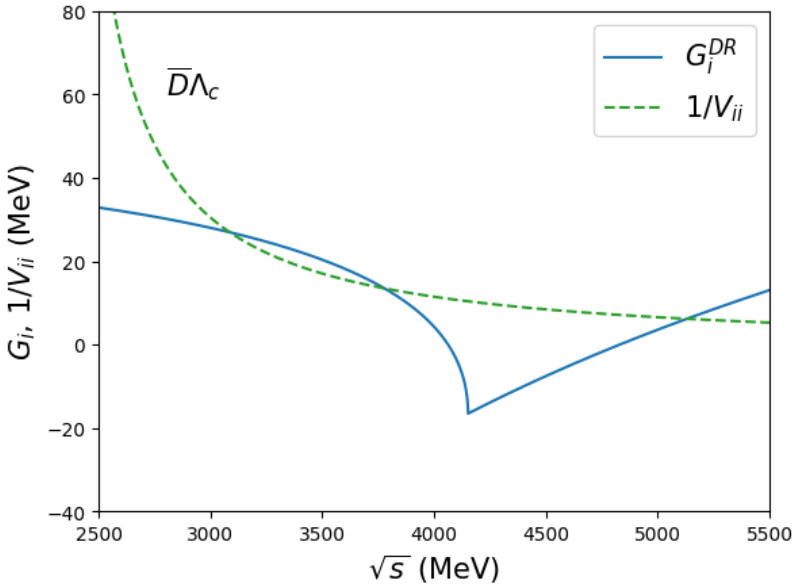
G^{HY} avoids the generation of unphysical poles

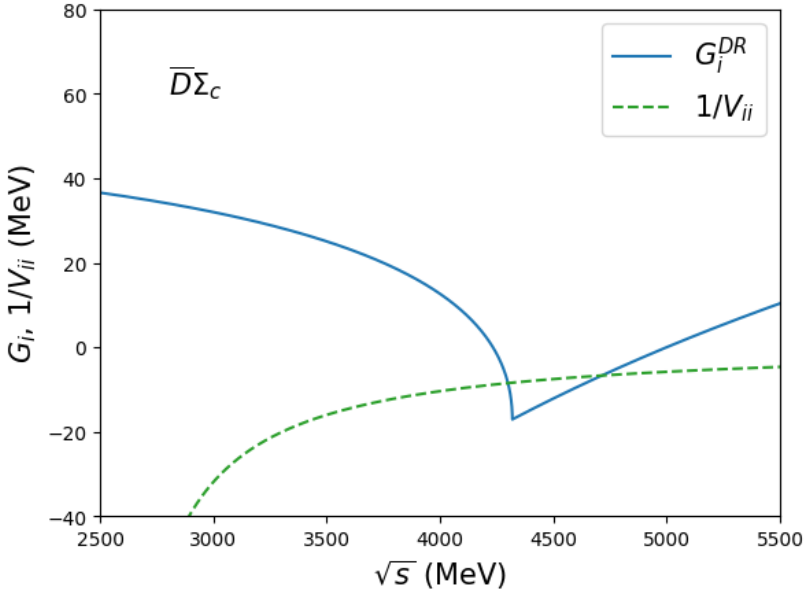
Sector $S = 0, I = 1/2$



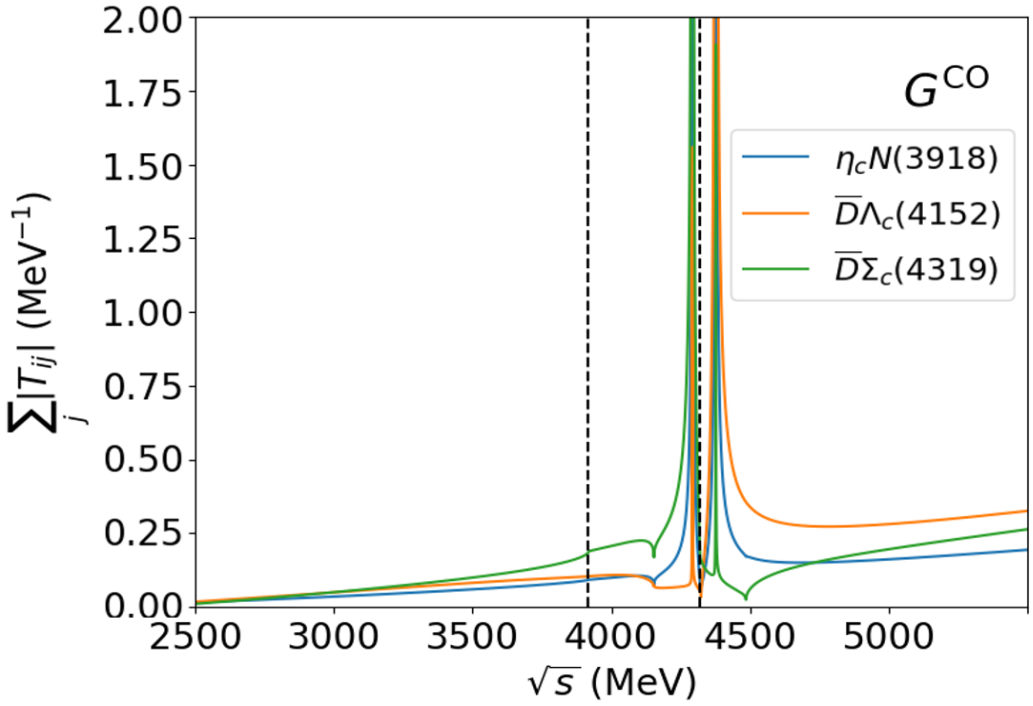
Sector $S = 0, I = 1/2$ (II)

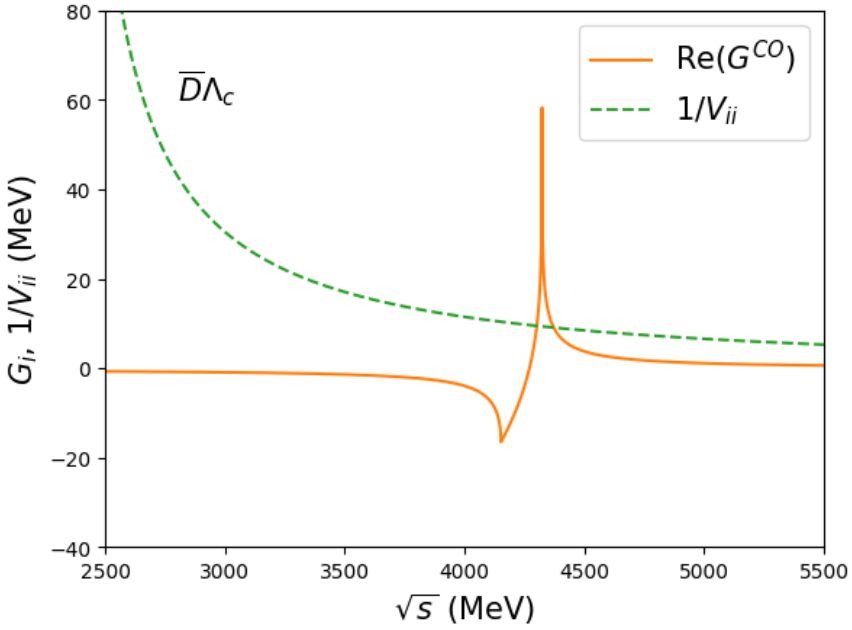


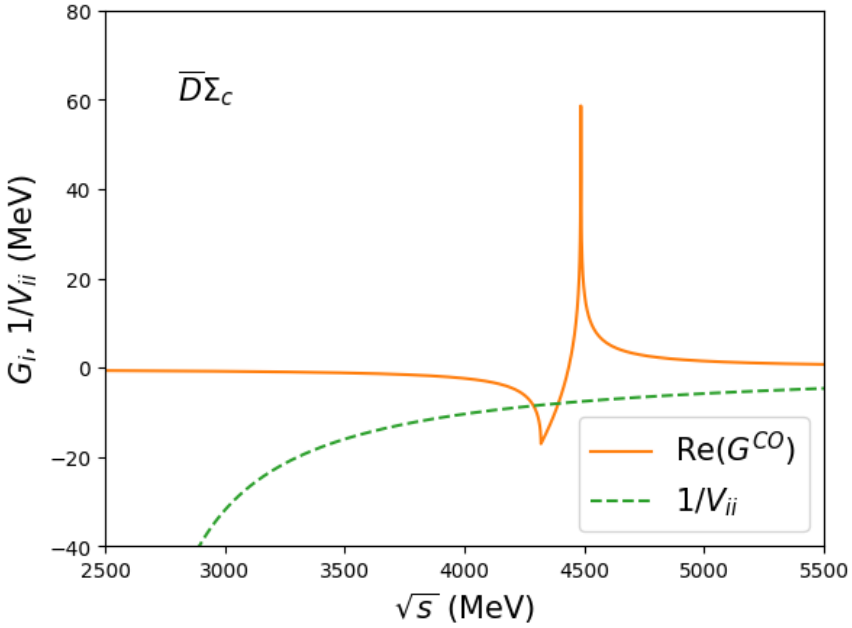




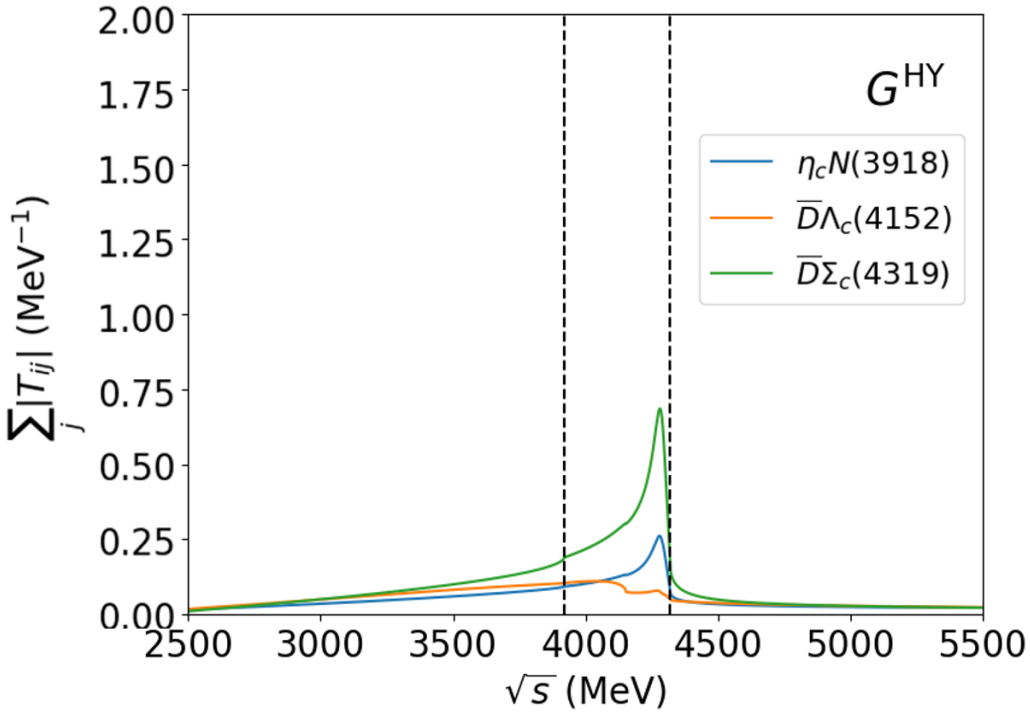
Sector $S = 0, I = 1/2$ (III)

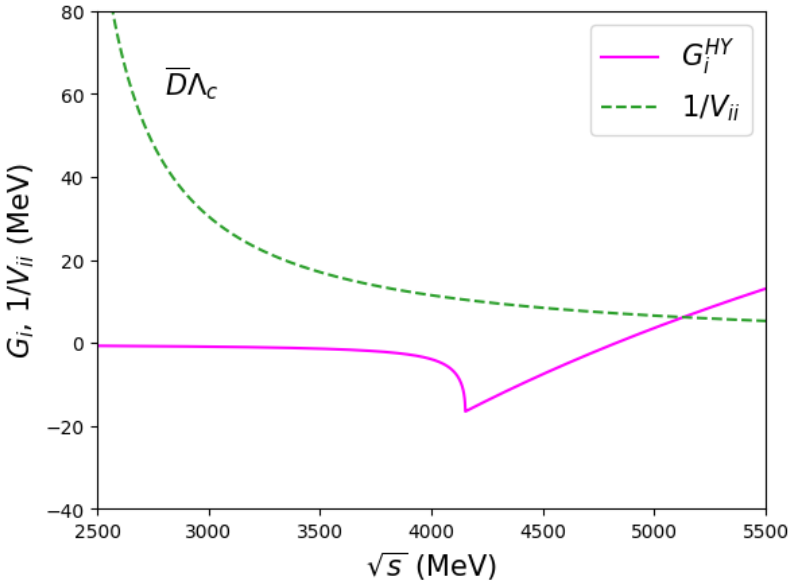


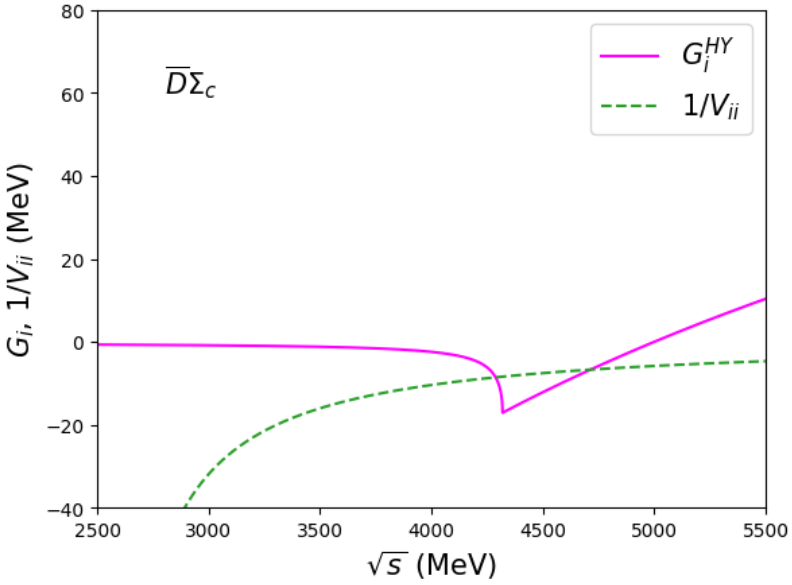




Sector $S = 0, I = 1/2$ (III)







Comparison with other theoretical studies

	Our model			Other works			
(S, I)	M	Γ	J^P	M	Γ	J^P	Reference
$(0, 1/2)$	4283	21	$1/2^-$	4265	23	$1/2^-$	Wu, Molina, Oset & Zou, PRC (2011)
	4422	30	$1/2^-, 3/2^-$	4415	19	$1/2^-, 3/2^-$	
$(-1, 0)$	4189	0.3	$1/2^-$	4210	6	$1/2^-$	Wu, Molina, Oset & Zou, PRC (2011)
	4328	0.3	$1/2^-, 3/2^-$	4368	6	$1/2^-, 3/2^-$	
	4405	31	$1/2^-$	4398	16	$1/2^-$	
	4544	31	$1/2^-, 3/2^-$	4547	13	$1/2^-, 3/2^-$	
$(-1, 1)$				3602	0	$1/2^-$	Hofmann & Lutz, NPA (2005)
	4386	27	$1/2^-$				
	4527	28	$1/2^-, 3/2^-$				
$(-2, 1/2)$	4515	33	$1/2^-$	4493	74	$1/2^-$	Marsé-Valera, Magas & Ramos, PRL (2023)
	4654	30	$1/2^-, 3/2^-$	4633	80	$1/2^-, 3/2^-$	

PB + VB results

Local hidden gauge approach
based on SU(4) flavour symmetry

- Our results are consistent with those reported states in the literature

- New predictions in the $S = -1, I = 1$ sector

S=-1, I=1 PB channels: $\eta_c\Sigma$, $\bar{D}\Xi_c$, $\bar{D}_s\Sigma_c$ and $\bar{D}\Xi'_c$

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	Our model			Other works			
$(S,\, I)$	M	Γ	J^P	M	Γ	J^P	Reference
$(0,\, 1/2)$	4283	21	$1/2^-$	4265	23	$1/2^-$	Wu, Molina, Oset & Zou, PRC (2011)
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$(-1,\, 0)$	4189	0.3	$1/2^-$	4210	6	$1/2^-$	Wu, Molina, Oset & Zou, PRC (2011)
	4328	0.3	$1/2^-, 3/2^-$	4368	6	$1/2^-, 3/2^-$	
	4405	31	$1/2^-$	4398	16	$1/2^-$	
	4544	31	$1/2^-, 3/2^-$	4547	13	$1/2^-, 3/2^-$	
$(-1,\, 1)$				3602	0	$1/2^-$	Hofmann & Lutz, NPA (2005)
	4386	27	$1/2^-$	Fake pole!			
	4527	28	$1/2^-, 3/2^-$				
$(-2,\, 1/2)$	4515	33	$1/2^-$	4493	74	$1/2^-$	Marsé-Valera, Magas & Ramos, PRL (2023)
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Comparison with other theoretical studies

	LHGA-SU(4)			LHGA-WF			Other works			
$(S,\ I)$	M	Γ	J^P	M	Γ	J^P	M	Γ	J^P	Ref.
$(0,\ 1/2)$	4283	21	$1/2^-$	4286	9	$1/2^-$	4265	23	$1/2^-$	[30]
	4422	30	$1/2^-, 3/2^-$	4353	0	$3/2^-$	4415	19	$1/2^-, 3/2^-$	[30]
				4425	10	$1/2^-, 3/2^-$	4306	15	$1/2^-$	[31]
				4492	0	$1/2^-, 3/2^-, 5/2^-$	4374	6.9	$3/2^-$	[31]
							4452	3	$3/2^-$	[31]
							4453	23	$1/2^-$	[31]
							4519	14	$3/2^-$	[31]
							4519	0	$5/2^-$	[31]
							4520	22	$1/2^-$	[31]
$(-1,\ 0)$	4189	0.3	$1/2^-$	4189	0	$1/2^-$	4210	6	$1/2^-$	[30]
	4328	0.3	$1/2^-, 3/2^-$	4328	0	$1/2^-, 3/2^-$	4368	6	$1/2^-, 3/2^-$	[30]
	4405	31	$1/2^-$	4409	10	$1/2^-$	4398	16	$1/2^-$	[30]
	4544	31	$1/2^-, 3/2^-$	4480	0	$3/2^-$	4547	13	$1/2^-, 3/2^-$	[30]
				4548	10	$1/2^-, 3/2^-$	4199	0.2	$1/2^-$	[28]
				4619	0	$1/2^-, 3/2^-, 5/2^-$	4338	0.2	$1/2^-, 3/2^-$	[28]
							4423	15	$1/2^-$	[28]
							4489	0	$3/2^-$	[28]
							4566	31	$1/2^-, 3/2^-$	[28]
							4627	0	$1/2^-, 3/2^-, 5/2^-$	[28]
$(-1,\ 1)$	4386	27	$1/2^-$	4392	8	$1/2^-$				
	4527	28	$1/2^-, 3/2^-$	4461	0	$3/2^-$				
				4533	9	$1/2^-, 3/2^-$				
				4602	0	$1/2^-, 3/2^-, 5/2^-$				
$(-2,\ 1/2)$	4515	33	$1/2^-$	4521	9	$1/2^-$	4493	74	$1/2^-$	[16]
	4654	30	$1/2^-, 3/2^-$	4607	0	$3/2^-$	4633	80	$1/2^-, 3/2^-$	[16]
				4661	10	$1/2^-, 3/2^-$	4535	9	$1/2^-$	[17]
				4747	0	$1/2^-, 3/2^-, 5/2^-$	4602	0	$3/2^-$	[17]
							4675	10	$1/2^-, 3/2^-$	[17]
							4743	0	$1/2^-, 3/2^-, 5/2^-$	[17]

Comparison with experimental data

	Our model			PDG		
$(S,\, I)$	M [MeV]	Γ [MeV]	J^P	M [MeV]	Γ [MeV]	J^P
$(0,\, 1/2)$	4283	21	$1/2^-$	$4312^{+7}_{-0.9}$	10 ± 5	-
				4380 ± 30	210 ± 90	-
	4422	30	$1/2^-, 3/2^-$	4440.3^{+4}_{-5}	$20.6 \pm 4.9^{+8.7}_{-10.1}$	-
				$4457.3^{+4}_{-1.8}$	$6.4 \pm 2^{+5.7}_{-1.9}$	-
$(-1,\, 0)$	4189	0.3	$1/2^-$			
	4328	0.3	$1/2^-, 3/2^-$	4338.2 ± 0.8	7.0 ± 1.8	$1/2^-$
	4405	31	$1/2^-$	$4458.8^{+6}_{-3.1}$	$17.3 \pm 6.5^{+8}_{-5.7}$	-
	4544	31	$1/2^-, 3/2^-$			
$(-1,\, 1)$	4386	27	$1/2^-$			
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	4544	31	$1/2^-, 3/2^-$			

- **5** out of **6** exotic baryons can be associated to a molecular state.
- The $P_c(4380)^+$ cannot be associated to any of our predicted states due to its large width.
- Further fine tuning of the parameters is necessary

Conclusions

- We introduce a new regularization procedure of the loop function, G^{HY}, which enables a cleaner unitarization of the scattering amplitude by avoiding the generation of unphysical poles

- The generated states are in agreement with those predicted within the G^{DR} and G^{CO} schemes. Also no significant differences is found with the states reported in other theoretical works

- **5** out of **6** experimental states with hidden charm could be assigned with the states predicted within our approaches, but further parameter tuning is necessary

- Our complete study of hidden charm pentaquarks with an improved unitarization method predicts 3 posible $S = -1, I = 1$ states

- No recent theoretical predictions in the $S = -1, I = 1$ sector have been found. This lack of information is most probably be related to the complex structures of the T-matrix when using G^{DR} or G^{CO}

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G^{HY} simplifies pole analysis a lot!